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PRELIMINARY DESIGN OF AN OFFSHORE WIND SYSTEM FOR MALAYSIA

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ABSTRACT

The purpose of this paper is to conduct preliminary studies for an offshore wind farm project off the Malaysian coast. To this end, a study of actual wind turbines is conducted to better understand the issues of the project, then, an existing market research of a wind turbine model sufficient for the implantation site. Moreover, to estimate the costs of the project, a financial study on wind turbines was conducted. Finally, a study of the support structures for the wind farm was proposed.

Keywords: *Renewable energy, wind turbine, wind power, offshore*

1.0 INTRODUCTION

Environment issues are probably the biggest global concern we face nowadays. It has leaded the world to give serious consideration to developing renewable energy. Like many other countries, Malaysia is currently being heavily dependent on fossil oil and natural gas. These sources of energy are becoming problematic due to their finite aspect (which leads to higher prices) and their impact on the environment. In 2016, the fossil fuel industry released nearly 35 Billion tons of CO^2 into the atmosphere [1].

As shown in Figure 1, fossil sources of energy play a dominant role in the electricity generation in Malaysia. Figure 2 on the other hand, presents the worldwide main renewable energy (RE) sources production to the million tonnes oil equivalent. With the country only has 33 years of natural gas reserves and 19 years of oil reserves, it is one of reasons that push the Malaysian government to try and shift into renewable energy sources [2]. The country also has already built its own alternative energy program [3].

Renewable energy is energy collected from renewable resources, which is inexhaustible in a human timescale, such as sunlight, wind, rain, waves and tides [4]. The urge to develop sustainable and clean sources of energy, and increase their share in the energy production has led many countries to invest in this field. In 2015 286 billion USD have been invested worldwide in renewables. These

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energy sources contributed 23.7% to global electricity production this year [5]. This share was to 19.5% in 2009 [6].

However, in Malaysia, due to a lack of strong political support, the development of renewable energies is notably slow, where the fossil fuel industries are still heavily subsided. Although the government levies taxes on electricity consumption to fund the development of renewables, the share of non-hydroelectric RE in the total power productions remains low (3% as shown in Figure 1). Two wind power generations projects conducted by the government already failed. Many wind studies in Malaysia have relied on poor data or inadequate methodologies, resulting in inaccurate estimates of wind potential [7].

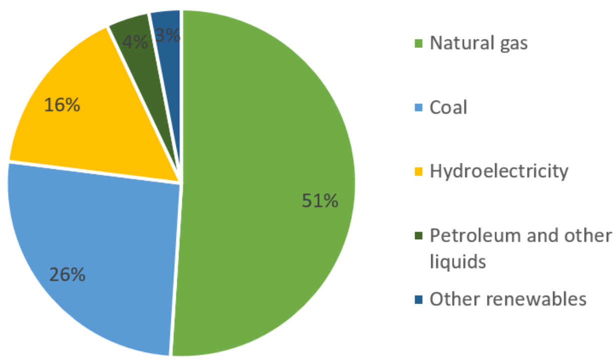


Figure 1: Malaysian electricity generation in 2015 [8]

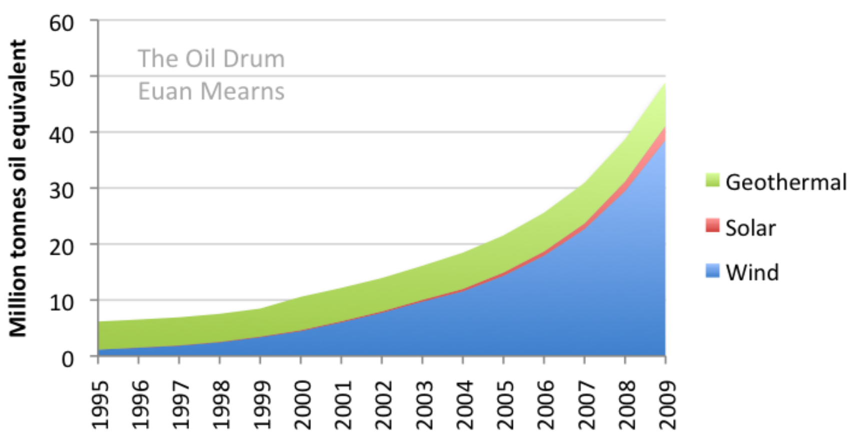


Figure 2: Worldwide main RE sources production [9]

Offshore wind energy could be one of the alternative ways to generate power, as there is huge offshore wind potential, especially during the monsoon season [3]. In order to develop and conduct a sustainable wind power project, it is primordial to choose the adequate wind turbine for the installation. The best wind turbine must meet the expectations of the project according to the Malaysian needs. It will be chosen based on the factors including wind speed, power output, energy generation, costing and reliability. Different parameters must be studied, both technical and financial parameters.

The first step of the study is a research on the wind power technology, and more especially on the different types of wind turbines. Then the different parameters of the projects are determined. The objectives are defined according to the expectations of the project. After that, potentially suitable wind turbines are listed, and classified according to their different characteristics. After dialog, deduction, and extensive research, the study is focused on fewer wind turbines. These turbines are submitted to the economic study of the project.

2.0 OFFSHORE WIND

2.1 Wind power

Wind power is the use of air flow to produce electric power. There are many advantages of the use of wind power to produce electricity. In addition to be a clean and renewable energy, it is available everywhere on earth and its capacity of power generation is one of the highest of renewable energy resources.

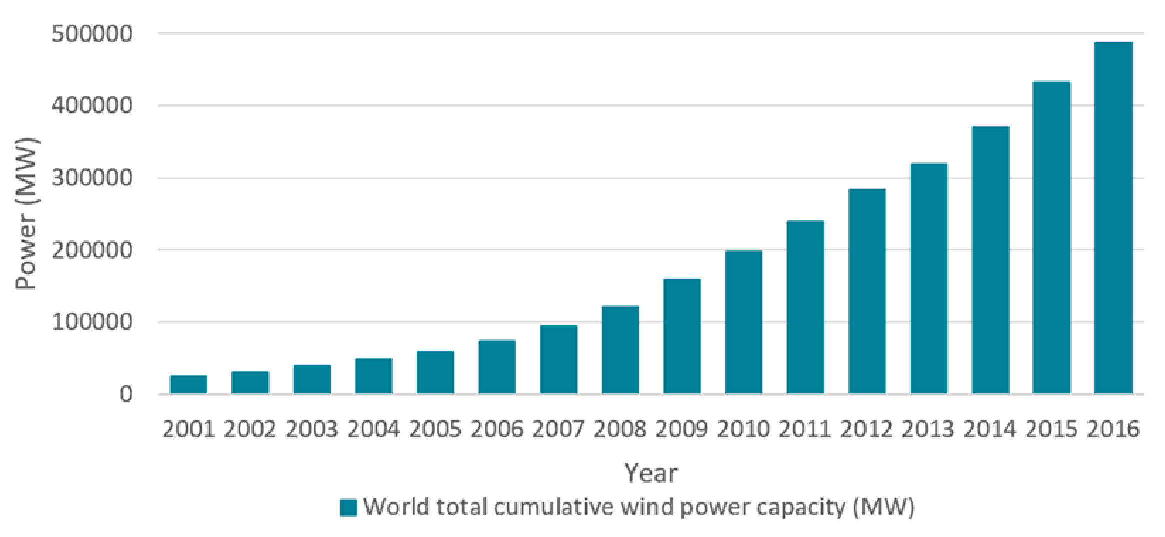


Figure 3: Evolution of the global wind power capacity [10]

The main disadvantage of wind power is its variability on several time scales as days or seasons. The availability of wind power may not follow the variations of energy demand. During low wind period it must be complemented with other power sources to insure the electricity supply. This implementation of other sources of power is a challenge as the goal is to prevent power shortage during low wind period, which are not predictable, and to supplement them with other power sources [11].

Wind power is harvested by wind turbines. The wind turbine functioning is as follows [12]:

1. The wind flow over the blade of wind turbine
2. As the wind encounter the blades, they start rotating
3. The rotation of the blades, linked by a rotor, a shaft and a gearbox to a generator, spin the generator to produce electricity.
4. The turbine is linked to a transformer to increase the voltage
5. The electricity is sent to distribution lines with local transformers to lower the voltage
6. Finally, the electricity with appropriate domestic voltage is available for public use

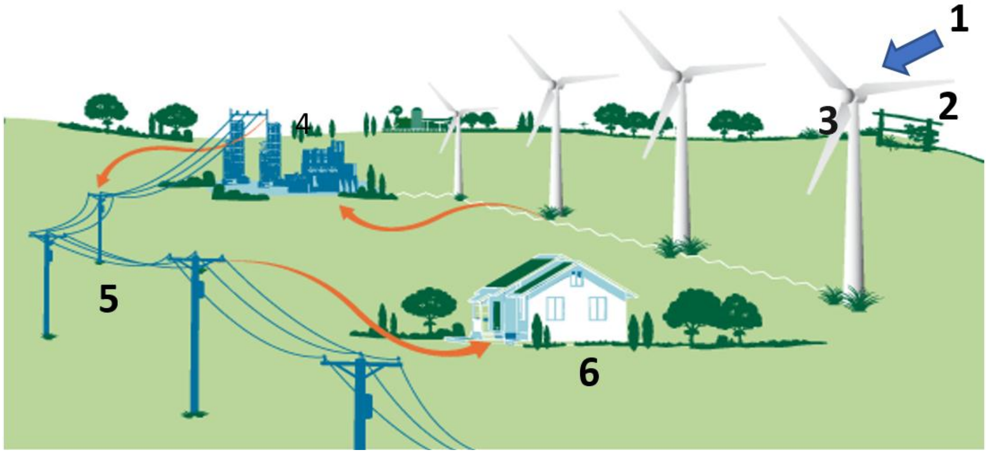


Figure 4: Wind energy parkour [12]

The harvested energy is the kinetic energy E_c (kg.m²/s²) of air flow, also called wind. It can be defined as:

$$E_c = \frac{1}{2}mv^2 = \frac{1}{2}\rho_a \upsilon_a v^2 \quad (1)$$

Where m is the mass of moving air (kg), v is the wind speed (m/s), ρ_a is the density of air (kg/m^3) and υ_a the volume of air (m^3).

Power is energy per unit time. For wind power, it can be defined as:

$$P = \frac{E_c}{t} = \frac{1}{2}\rho_a A v^3 \quad (2)$$

Where E_c is the wind energy (kg.m²/s²), ρ_a is the air density (kg/m^3), A the area of wind interacting with the air parcel (m²), and v the wind speed (m/s).

However, the wind power is different from the actual power that is obtainable from a wind turbine P_t:

$$P_t = (C_{PW}\varepsilon_g\varepsilon_b)\frac{1}{2}\rho_a A v^3 \quad (3)$$

With, C_{PW} the coefficient of performance (also called power coefficient), ε_g the generator efficiency, ε_b the gearbox / bearings efficiency, ρ_a the air density (kg/m^3), A the area of wind interacting with the air parcel (m²), and v the wind speed (m/s) [13].

Depending on their use, wind turbine can generate power on different scale. Indeed, it can generate electricity for an average household (turbine 4), 200 houses (turbine 3), 500 houses (turbine 2) or even 1000 houses (turbine 1) (see Figure 5) [14].

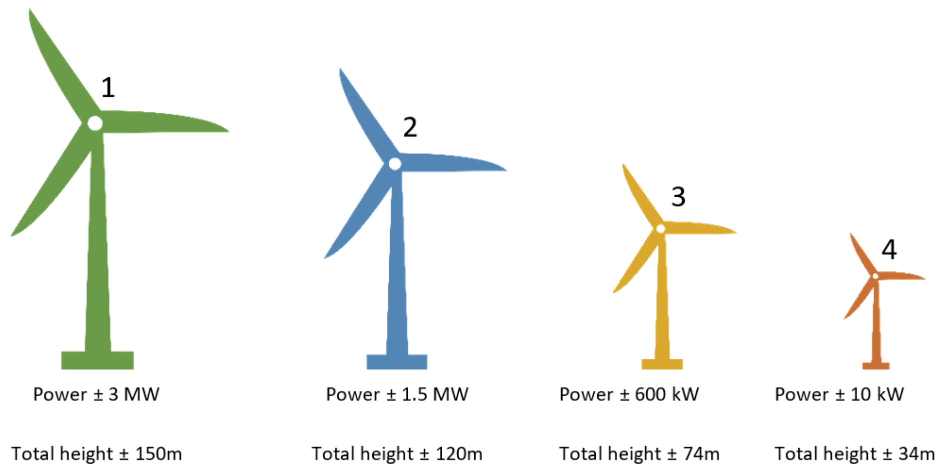


Figure 5: Different scales of wind turbine [14]

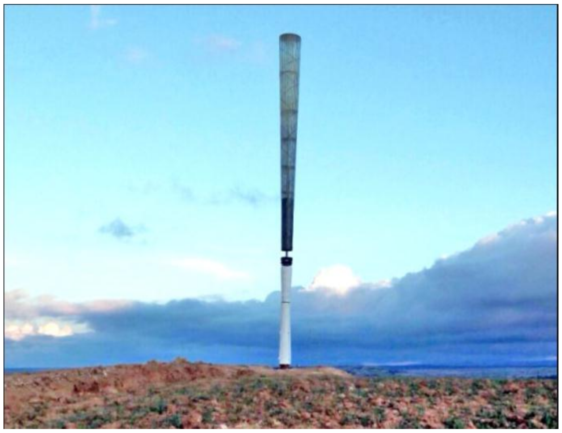
2.2 The different types of wind turbine

Table 1 summarizes the different types of wind turbine in the current market and their advantages and disadvantages. Meanwhile, Figure 6 presents the example of available wind turbine models in the market.

Table 1: Different types of wind turbine

Type & Features	Advantages/Disadvantages
Bladeless • Invented by David Yanes, was convinced that if wind can deliver such amount of energy to a structure, we could use it to our advantage [15] • Unique type of turbine – does not involve any rotation in the wind energy harvesting process • Working principle due to the Vortex Induced Vibration (VIV) • Composed of fewer parts - without gears or any moving parts in contact, no friction is induced in the system, no oil is needed during operating.	✓Significantly lighter especially if it is planned with floating platforms ✓Maintenance costs are drastically reduced compared to any other type of wind turbine ✓Solve an environment issue that conventional turbines face – killing birds × However, part of the energy provided by the oscillations would be absorbed by a not enough steady platform that would oscillate too × Less efficient - efficiency of 70% at best while the current rotating turbine can go up to 90% × The models are still in development phase – few prototypes that already exist have no precise specifications regarding their performances × It is difficult to tell if they are suitable for low wind areas (mean wind speed between 4 and 6 m/s)

Vertical Axis Wind Turbine (VAWT) • Working principle: Variation of the interactions between its blades and the wind • Two main types: Savonius and Darrieus • The wind acts differently from one blade to another depending on the angle of the blade, inducing the torque, allowing rotation • These types of turbine can't start automatically, and need to be orientated before they can operate – can be solved by combining several turbines in one.	✓ composed of fewer parts and their main components (gearbox, generator) can be placed at the base of the structure - facilitates maintenance operations, especially on an offshore installation ✓ When operating, VAWT can work regardless of the wind direction, without any wind sensing or orientation mechanism ✓ VAWT are suitable at a small scale, for urban and residential areas for private individual's installations ✗ However, forces acting on the system are more turbulent than these acting on an HAWT, inducing important torque variations, and bending moments ✗ most of the models that are already in function require important props such as thick wires or bars to sustain their structure ✗ VAWT can't be as efficient as HAWT – only a fraction of their blades generate torque as the rest are completing the rotation
Horizontal Axis Wind Turbine (HAWT) • Working principle: rotation axis oriented horizontally to the wind • Main rotor shaft and electrical generator are located at the top of a tower • Most have a gearbox, which turns the slow rotation of the blades into a quicker rotation that is more suitable to drive an electrical generator • The rotor is designed aerodynamically to capture the maximum amount of energy out of the wind • The blades are lightweight, durable and corrosion-resistant material • The best materials are composites of fiberglass and reinforced plastic • The gear box amplifies the energy output of the rotor, it is situated directly between the rotor and the generator • The generator produces electricity from the rotation of the rotor	✓ It has self-starting ability – it does not require any external power source to start ✓ Functioning in a wide range of wind speed, it has a highest efficiency compared to any other type of wind turbine ✓ Since all blades of this turbine work simultaneously, so it is capable of extracting maximum energy form the wind ✓ Components are easily removed for maintenance purpose ✗ They must be oriented according to the wind direction to operate and can be pointed out of it



(a) Bladeless wind turbine
(https://www.technologyreview.com)

(b) Horizontal axis wind turbine
(https://strategy2050.kz)

(c) Savonius wind turbine
(https://nevadanscleanenergy.org)

(d) Darrieus wind turbine
(https://www.dreamstime.com)

Figure 6: Available wind turbine model in the market

3 TECHNICAL STUDY

3.1 Parameters

Several technical parameters must be considered to make a preliminary assessment of the suitability of the turbines;

i. The rated power is the maximum power output the turbine. It is proportional to the size of the turbine. It can go from around 20 Watts for very small turbines, used on sailboats for example, to more than 8 MW for the largest offshore wind plant installations.
ii. The diameter of the rotor usually depends on the rated power. The larger is the rotor, the more energy the turbine would be able to harvest, but the smaller the number of turbine we can install in a same sized area. Rotor diameters lie between less than 1 meter for small turbine and more than 150 meters for the largest one.
iii. The cut in wind speed is the minimum speed of wind the turbine requires to generate power. This parameter is very important as it is primordial that the wind turbine work at low wind speed to be reliable in areas with mean wind speed between 4 and 6 m/s like along the

Malaysian coast. For the same reasons, the power output at given wind speed is also very important. It gives us the power curve

iv. The power curve of each turbine enables to estimate the annual energy production for a given annual mean wind speed. Figure 7 for example shows the power curve of the STOMA STK 100 kW turbine. For a 100kW turbine at 5 m/s annual wind speed, it can be expected to generate around 250 000 kWh of power output.

v. The capacity factor of a wind turbine is given at a certain wind speed. It describes the capacity of the turbine to harvest the wind energy compared to its rated power. A good capacity factor lies between 20 and 30%. Above, it is excellent.

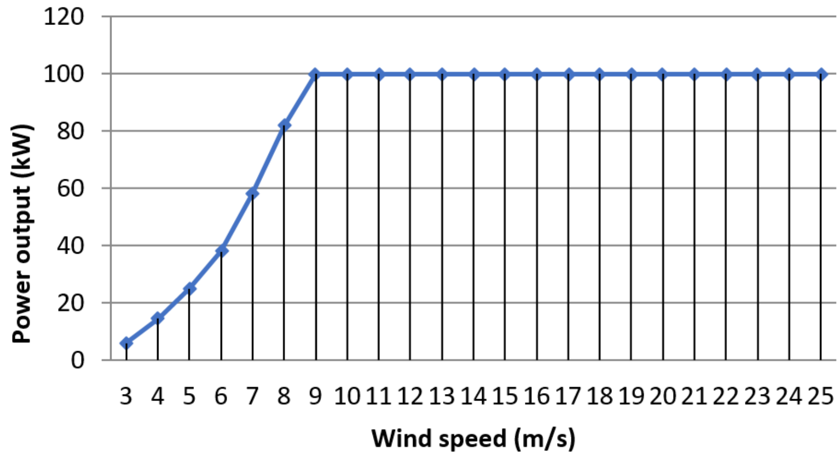


Figure 7: Power curve of the STOMA STK 100kW

3.2 Location

Wind turbine projects depend on many parameters, but the main issue is the wind speed. Indeed, the wind turbine efficiency and its energy production depend on the wind speed, as shown on Figure 8. The average wind turbine provides the maximum of power with a wind speed from 12 to 15 m/s (rated wind speed).

This wind speed influence can be demonstrated by the formula traducing the power output of the wind turbine:

$$P_t = (C_{PW}\varepsilon_g\varepsilon_b)\frac{1}{2}\rho_a A v^3 \tag{4}$$

With, P_t the power that is obtainable from a wind turbine (Kw), C_{PW} the coefficient of performance (also called power coefficient), ε_g the generator efficiency, ε_b the gearbox / bearings efficiency, ρ_a the air density (kg/m^3), A the area of wind interacting with the air parcel (m^2), and v the wind speed (m/s) [13]. This formula shows that the power P_t is proportional to the speed cubed, therefore, the wind speed has an extreme influence on the power generation.

For this reason, it is primordial to assess the wind potential of the location. In Malaysia, the wind speed is low. The mean wind speed along the Malaysian cost lies between 4 m/s and 6 m/s. Figure 9 and Table 2 show the wind speed depending on the location. The location must meet the following requirements; sufficient annual mean wind speed ($\geq$ 4 m/s) and recommended to be close enough to the coastline (maintenance operations and connection to the grid). Thus, the area chosen is D11 which correspond to the Sabah's coast up to the north-east coast of Borneo (refer to Figure 10).

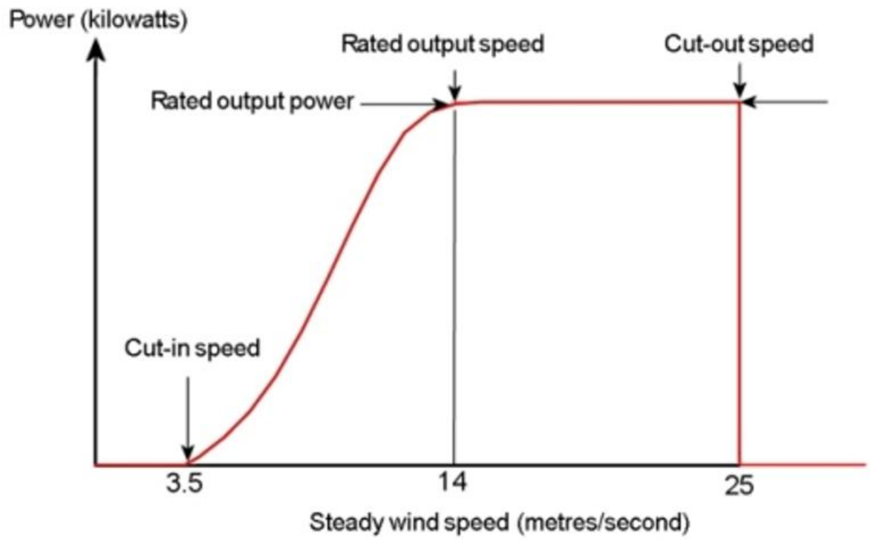


Figure 8: Typical power output for wind turbine depending on the wind speed
(Source: wind-power-program.om)

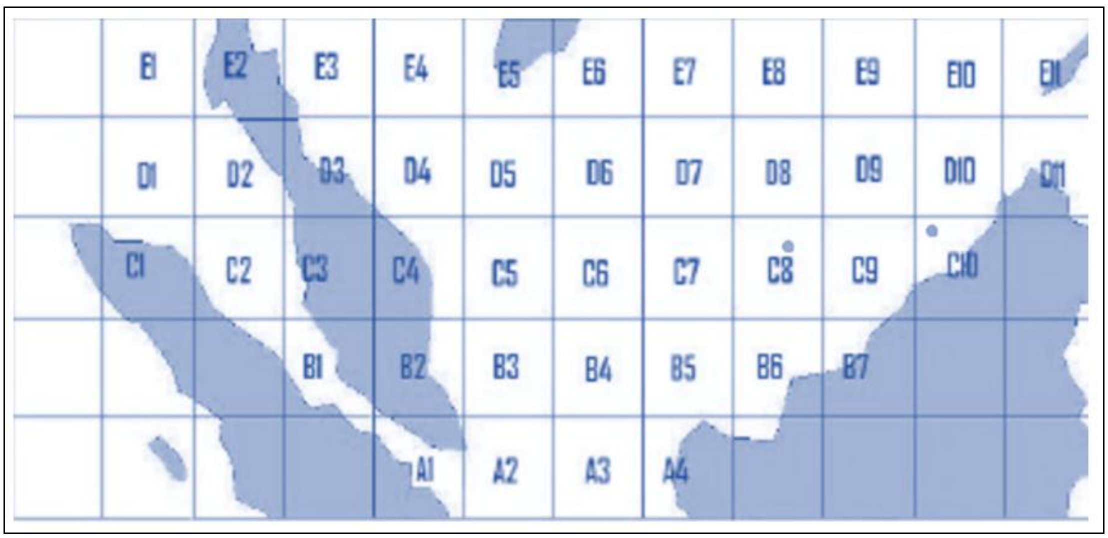


Figure 9: Malaysia and South China Sea gridded map [3]

Table 2: Annual mean wind speed in Malaysia [3]

Area	Annual mean wind speed (m/s)	Area	Annual mean wind speed (m/s)
A1	2.629	**C6**	5.015
A2	4.205	**C7**	4.581
A3	4.244	**C8**	4.341

A4	3.718	**C9**	5.150
B1	2.918	**C10**	4.105
B2	4.135	**D1**	4.313
B3	4.541	**D2**	3.614
B4	4.355	**D3**	4.073
B5	3.865	**D4**	4.760
B6	3.622	**D5**	5.473
B7	3.456	**D6**	5.912
C1	3.434	**D7**	6.036
C2	3.041	**D8**	5.924
C3	2.725	**D9**	5.239
C4	5.364	**D10**	4.899
C5	5.084	**D11**	5.165

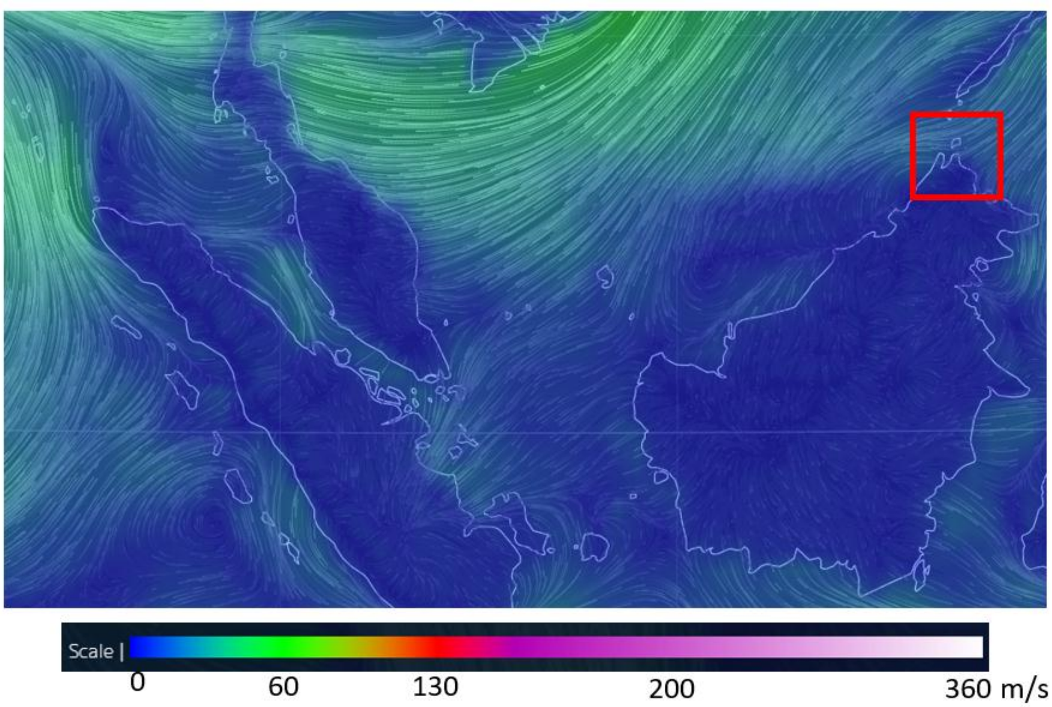


Figure 10: Wind flows and final location (D11)

3.3 Wind turbines

The main technical parameters that will characterize the potentially suitable turbines are stated. Then the technical characteristics and performances of several wind turbines available on the market are gathered and classified in a data base. They are selected according to their potential suitability for the establishment of a small scaled offshore wind power installation along the Malaysian coast. As the offshore wind in Malaysia does not exceed annual mean speed of 6 m/s [3], these turbines must show acceptable performances in low wind speed conditions. The selection was mainly based on the power curve and the estimated annual energy production in a 5 m/s annual wind speed area.

After discussion, the decision to narrow down the study to turbines between 60kW and 100kW has been made. In order to have more specification about the turbines, several manufacturers have been contacted. Thanks to the interchange of information, the list has been narrowed down to 6 wind turbines (refer to Table 3). These 6 wind turbines have been submitted to the economic analysis.

Table 3: Wind turbine selected for the financial analysis

Turbine	RD (m)	Rated Power (kW)	Hub Height (m)
ErgoWind 60	16	60	24
NPS-100C	24	100	37
Stoma STK60/D21	22	60	34
Aeolos H-60	22	60	30
NPS-60C	24	60	37
ATB 60.28	28	60	37

4 ECONOMIC ANALYSIS

4.1 Layout and number of turbine

The total rated power of the installation is the maximum power output of the plant. It is factor of the number of wind turbine generator (WTG) of the installation and the rated power of each WTG. The layout of the turbines in the park as illustrates in Figure 11 follows the rule of the thumb. The rule specifies that the turbines must be spaced from 4 to 6 times the rotor diameter in the transversal direction of the prevailing wind, and from 7 to 9 times the rotor diameter in the direction of the prevailing wind. Many studies suggest 5 times in transversal direction to the prevailing wind and 7 times in the direction of the prevailing wind as the more optimized layout [16].

This disposition determines the number of turbines that can be install in a 1 km by 1 km area, according to the following formula:

$$N = \left(\frac{1000}{5 * RD}\right)\left(\frac{1000}{7 * RD}\right) = \frac{10^6}{35 * RD^2} \quad (5)$$

Where RD is the rotor diameter (m). Table 4 tabulates the rotor diameter of selected turbines in this study and the number of WTG.

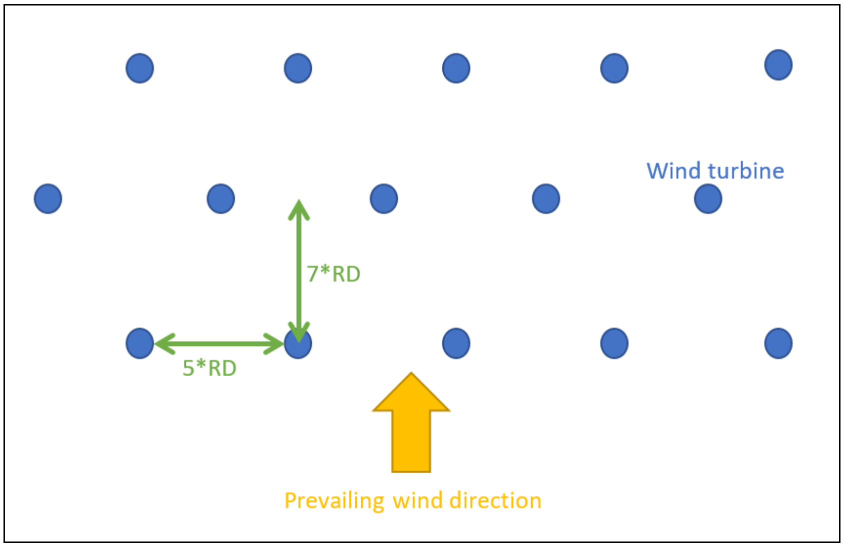


Figure 11: Rows of wind turbines installed according to the rule of thumb

Table 4: Number of WTG depending on the rotor diameter, RD (m)

Turbine	RD (m)	Number of WTG
Stoma STK60/D21	22	60
Aeolos H-60	22	57
NPS-60C	24	49
NPS-100C	24	49
ErgoWind 60	16	112
ATB 60.28	28	36

4.2 Different cost influencing the project cost

To assess the economic feasibility of an offshore wind plant project the total investment cost must be estimated. Figure 12 describes three main parameters in the economic analysis of offshore wind power plant. The three parameters are turbine cost (C_t), electrical system cost (C_e) and grid cost (C_{gi}). Besides, there is a project and development cost (C_p) which constitutes about 4% of the total investment cost [17]. The total investment cost C_i is given by the following expression:

$$C_i = C_t + C_e + C_{gi} + C_p \quad (6)$$

4.2.1 Turbine cost, C_t

The following expression gives the totalized cost of the wind turbines in the installation.

$$C_t = N\left(C_{wt} * 1.1 + C_f * 1.5\right) \quad (7)$$

With N the number of WTG erected, C_{wt} the wind turbine cost and C_f the foundation cost. C_{wt} and C_f are respectively factored by a coefficient 1.1 and 1.5 as the transport and installation are accounted for 10% of the WTG and 50% of the support structure cost [18]. Table 5 shows the cost of selected wind turbine and its foundation cost.

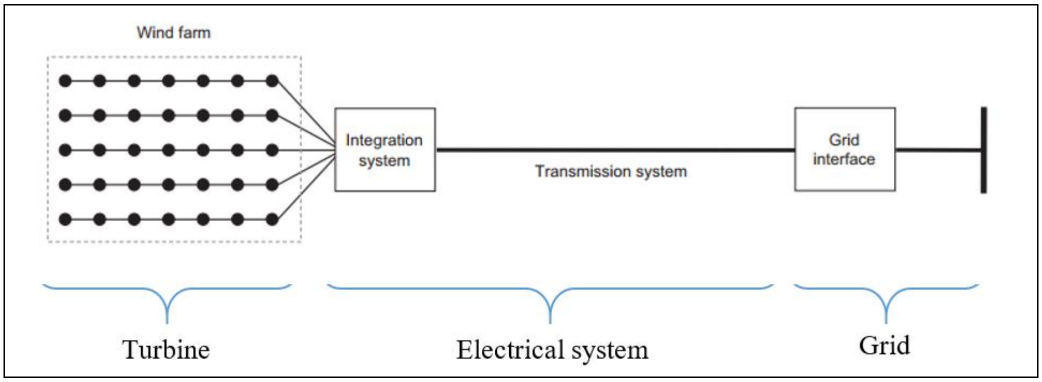


Figure 12: Cost repartition [18]

Table 5: Cost of the wind turbine and the foundation cost (RM)

Turbine	C_{wt} **(RM)**	C_f **(RM)**
Stoma STK60/D21	974 000	102 700
Aeolos H-60	515 000	102 680
NPS-60C	1 140 000	102 811
NPS-100C	1 185 000	171 351
ErgoWind 60	689 500	102 500
ATB 60.28	980 640	102 968

4.2.1.1 Cost of wind turbine (C_{wt})

The cost of the turbine depends mostly on the power output and the size of the turbine. It includes the tower, shell and electrical devices of the wind turbine generator. The purchasing cost does not appear on the provided specifications of the turbines. This information was collected by contacting the manufacturers of each turbine.

4.2.1.2 Foundation cost (C_f)

Foundation cost includes construction, material and installation cost. It is function of the number of turbines erected and depends on the water depth of the site and the hub height of the turbine. C_f can be estimated using the following formula [18]:

$$C_f = 320P_r[1 + 0.02(W - 8)]\left[1 + 0.8 * 10^{-6}\left(H\left(\frac{RD}{2}\right)^2 - 10^5\right)\right] \quad (8)$$

Where W is the water depth (m), H the hub height (m) and P_r the wind turbine rated power (kW).

4.2.2 Electrical system cost, C_e

The cost of subsea transmission cables in the park and between the park and the shore based station can be estimated at 464 RM/m. It includes the laying costs. The medium voltage transformer needed to connect the installation to the grid costs around 42.5 RM/kW. We can estimate the total cost of the OWF electrical installation as follows [19]:

$$C_e = 42.5 * P_{wf} + 464 * d \quad (9)$$

With P_{wf} is the total rated power in kW of the installation and d is the distances of cable laid. For this study, distance from the shore considered is 2 kilometres.

4.2.3 Grid interface cost, C*gi*

Regulation devices required to sustain the load variations of the system are estimated at 331 RM/kW. Monitoring and general control cost heavily depends on the implemented control actions. However, energy management systems are assumed to be equal to 322 RM/WTG. Therefore, the total cost of the grid interface can be estimated using the following expression [18]:

$$C_{gi} = 331 * P_{wf} + 322 * N \quad (10)$$

With P_{wf} is the total rated power in kW of the installation and N the number of WTG erected.

4.3 Cost of Energy (COE)

Table 9 tabulates the total investment cost for all turbines considered in this study in descending order (highest to lowest).

Table 9 : OWF costs for each WTG

Turbine	C_t (RM)	C_e (RM)	C_{gi} (RM)	C_p (RM)	C_i (RM)	Nb of WTG
ErgoWind 60	102 166 328	4 925 600	2 260 384	4 556 346	113 908 658	112
NPS-100C	76 465 818	3 456 250	1 637 678	3 398 323	84 958 069	49
Stoma STK60/D21	73 527 033	3 865 000	1 210 920	3 275 123	81 878 076	60
Aeolos H-60	41 069 628	3 857 350	1 150 374	1 919 890	47 997 242	57
NPS-60C	69 002 591	3 372 950	988 918	3 056 852	76 421 311	49
ATB 60.28	44 393 634	3 339 800	726 552	2 019 166	50 479 152	36

The Cost of Energy (COE) is then estimated in RM/kW and determines the economic feasibility of an energy generation project. The best wind turbine will provide lowest COE. The COE is calculated using the following expression;

$$\text{COE}: \frac{\text{Total Annualized Cost}}{\text{Annual Energy Production}} \tag{11}$$

The total annualized cost of the project is obtained by deviding the initial investment by the number of operating years of the OWF and adding the annual operating cost. Most of wind energy projects are assessed for an operating lifetime of 20 years. The annual operating costs are estimated at 2% of the initial investment cost [17]. Therefore we can estimate the COE using the following formula;

$$COE = \frac{\frac{C_i}{20} + 0{,}02 * C_i}{AEP} \tag{12}$$

With AEP is the Annual Energy Production of the wind farm and C_i the total investment cost. Figure 13 shows a comparison of the calculated COEs for each turbine. With an estimated cost production of 0.48 RM/kW, the Aeolos H-60kW seems to be the WTG producing the cheapest energy among all WTG considered in this study.

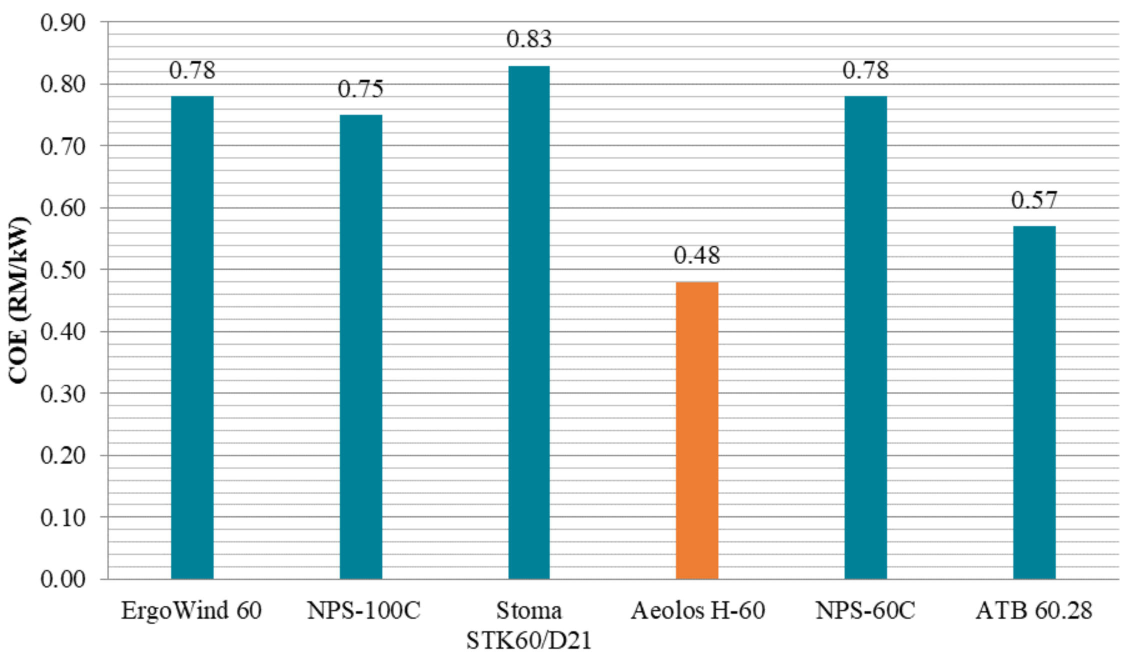


Figure 13: Cost of Energy (COE) by turbine

5 CONCLUSION

The main issue was to find a turbine that able to be adapted for low annual wind speed as the Malaysian the average wind speed is below 2 m/s. To this end, a study of actual wind turbines is conducted to better understand the issues of the project. Indeed, it is relevant to be familiar with what already exists and how it works to understand the issues and solutions of wind power. Then, an existing market research of a wind turbine model suitable for the implantation site specifications. Several wind turbines have been submitted to a technical and economic study.

The Aeolos H-60kW seems to fit both technical and financial requirements. Indeed, this turbine provide the lowest cost of energy among all the turbines that have been studied. With a capacity factor of 28.4% for an annual wind speed of 5 m/s, each turbine can generate up to 150 MWh per year. This wind turbine generator can provide the basis of Malaysian offshore wind energy production.

It would be relevant to assess more precisely the potential of such wind power project by software modelling. Computer simulation can provide valuable information to improve and optimize the parameters influencing the success of an offshore wind plant project.

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